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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

INVESTIGATION INTO THE EFFECTS OF USING DETONATING CORD TO REMOVE A CONVENTIONAL PROPELLER FROM A WATERBORNE SURFACE SHIP

by

J. H. Strandquist III

December 1984

Thesis Advisor: Y. S. Shin

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Investigation into the Effects of using Detonating Cord to Remove a Conventional Propeller from a Waterborne Surface Ship

by

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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ABSTRACT

The relation between the shock wave pressure on the propeller hub and the size of the detcord charge was determined experimentally by a series of shots conducted on a full-scale test platform. The shock-induced response of the shaft was measured directly with strain gages and accelerometers. Additionally, the experimental shock wave pressure data provided the basis for numerical prediction of the response profile of the shaft.

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To Jim Edwards: you're a good chess player. Thanks for all your help.

I. INTRODUCTION

The use of detonating cord ("detcord") in waterborne propeller maintenance has been practiced for many years by U. S. Navy diving and repair activities, with little knowledge of the potential effects on the shaft and related ship components. In order to quantify both the displacement and acceleration of the shaft caused by a detcord detonation on the propeller, a decommissioned Coast Guard cutter, ex-USCGC CAMPBELL (WHEC-32), was identified and chosen as a platform for the conduct of a series of test shots. The response of the shaft to these tests was measured, and the results are presented herein.

As provided for in the Naval Ships Technical Manual, [Ref. 1], detonating cord may be used to remove a damaged conventional propeller from a waterborne surface ship where drydocking or the use of alternative waterborne methods have been ruled out due to constraints in time, logistics, funding, or the tactical situation. The procedure is described in detail in [Ref. 2]. After clearing all interference (rope guard, fairwaters, and dunce cap removed; gland retaining ring moved forward as far as possible), the propeller hub boss nut is backed off several turns, as shown in Figure 1.1. Detcord is wound around the shaft against the forward face of the propeller hub a predetermined number of turns, or "wraps". To protect the shaft sleeve, the detcord is placed on top of an underlying layer of manila line. Several turns of line are also wound around the shaft between the propeller hub and the boss nut to cushion the impact there. When the charge is detonated, the impulse created by the pressure wave in the water overcomes the tremendous static friction between the propeller hub and the

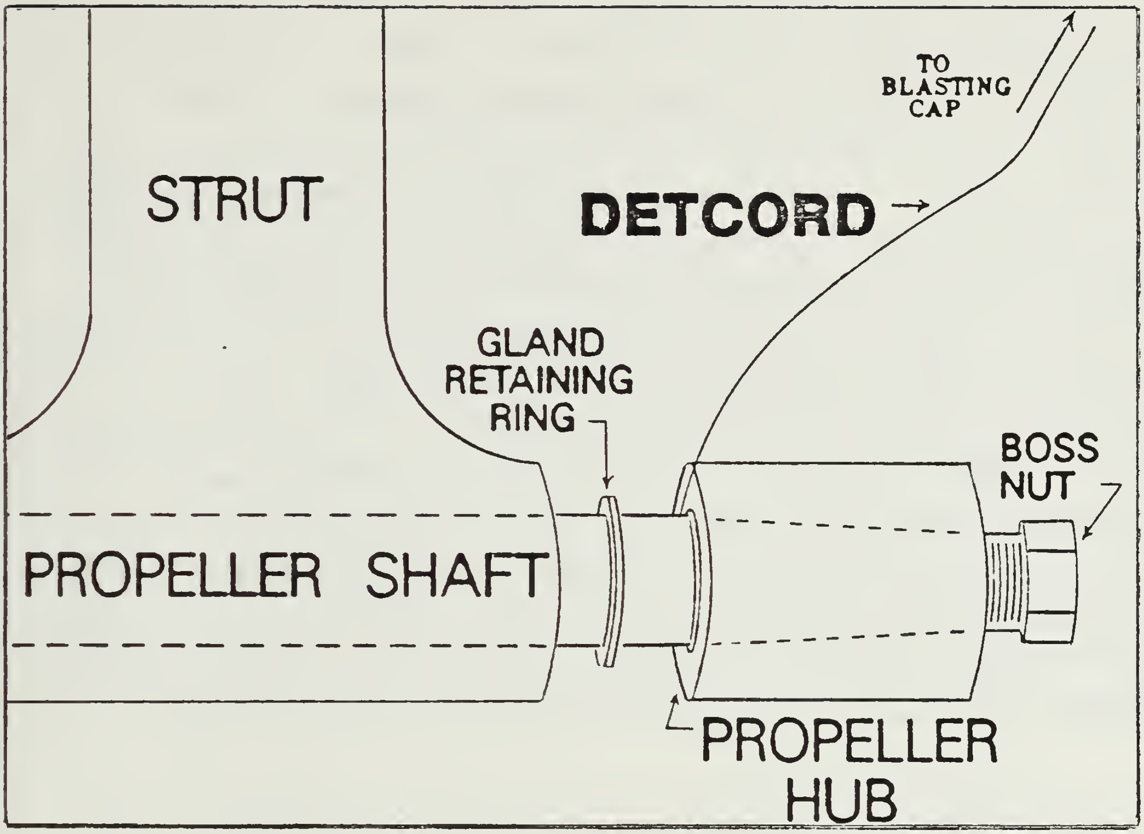


Figure 1.1 Underwater Propeller Removal Using Detcord.

shaft taper, and the propeller is pushed back along the shaft toward the boss nut. At this point the propeller replacement operation proceeds independent of the method used to loosen the damaged prop. See [Ref. 2] for more detail.

The following is quoted from [Ref. 3] :

> Detonating cord is round, flexible cord containing a center core of high explosive. The explosive core, usually pentaerythritol tetranitrate (PETN), is covered with various combinations of materials--these include textiles, waterproofing materials, and plastics which protect it from damage caused by physical abuses or exposure to extreme temperatures, water, oil, or other elements, and provide such essential features as tensile strength, flexibility, and other desirable handling characteristics....Detonating cord is relatively insensitive and requires a proper detonator...for initiation....As such, detonating cords are safe and reliable nonelectric detonating devices.

The detcord used in this thesis conforms with Military Specification Mil-C-17124C (Type I, Class e) [Ref. 4]. This "reinforced detcord" has a nominal explosive weight of 50 grains per foot, or about 7 pounds of explosive core per 1000 feet of detcord. According to several references, including [Ref. 3], the detonation velocity of 50 grain-per-foot detcord is on the order of 22,000 feet per second.

As a final note in this introduction, it was observed that the word "primacord" is used frequently in U. S. Navy literature, most notably in [Ref. 2]. It is pointed out here that "Primacord" is a registered trademark of the Ensign-Bickford Company [Ref. 5], which is not a sole-source vendor of detonating cord to the U. S. Government. It is recommended that future U. S. Navy publications dealing with the subject use the more appropriate generic term "detcord", which has wide acceptance among operating personnel.

II. THEORETICAL PREDICTIONS

A. SHOCK WAVE FROM AN UNDERWATER EXPLOSION

The nature of the shock wave near the surface of an explosive charge detonated underwater is not well understood, owing to the uncertainties in the equations of state in this region. It becomes very difficult, therefore, to predict the response of an assumed rigid body, in this case the propeller, from a contact or near contact underwater explosion. Empirical formulae for the shock wave pressure profile which have been derived to date are based primarily on tests conducted with spherical charges where the minimum target standoff distance was approximately five charge radii [Refs. 6,7].

An approximation of the pressure profile from an underwater explosion as a function of time after detonation is provided by [Ref. 6] :

$$P(t) = Pm[\exp(-Tr/\theta)] \qquad (2.1)$$

Here, Pm is the initial peak pressure, and θ is the time constant, defined as the time in milliseconds required for the shock to decay to Pm/e, or about one-third its maximum value. Both Pm and θ are functions of standoff distance. It was discovered during testing that for short distances θ is relatively insensitive to variations in standoff, and an average time constant was used. Equation 2.1 is generally considered to be a close approximation of the actual shock profile for about one time constant; beyond this point, it usually can be relied upon to provide only a rough estimate, although in the present case it appears to have been a very good one (see Appendix A).

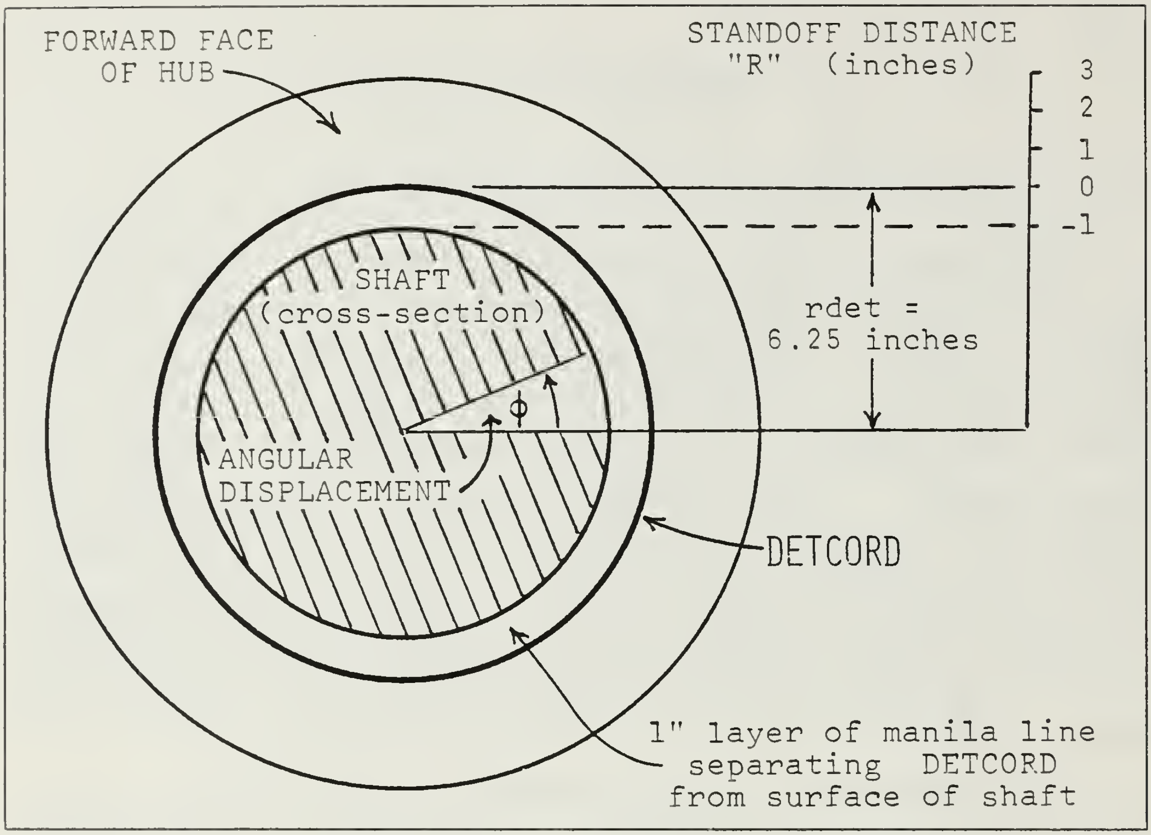


Figure 2.1 Propeller Hub Geometry (USCGC CAMPBELL).

The retarded time Tr in equation 2.1 is defined by the charge geometry for the test platform illustrated in Figure 2.1, and must account for a finite detonation velocity. For example, if the detonation process commences at $\phi = 0°$, it will take approximately 0.15 milliseconds to complete the process at $\phi = 360°$. Thus,

$$Tr = t - (|R|/c) - [(rdet)(\phi)/Dv] \qquad (2.2)$$

where

t = real time from initial detonation (msec)

R = radial standoff distance between detcord and point of interest

c = speed of sound in water (nominally five feet per msec)

rdet = radius of detcord charge

ϕ = angular distance from point of initial detonation to point of interest

Dv = detonation velocity of 50 grain-per-foot detonating cord

Note that if Tr < 0 [i.e., $t < |R|/c + (rdet)(\phi)/Dv$], physical reasoning tells us that the pressure at such times is equal to zero (or more precisely, hydrostatic pressure, although this is negligible at propeller depths).

When the shock wave from an underwater explosion contacts a rigid structure, the pressure at the surface is primarily the sum of the incident free-field pressure wave and the reflected pressure wave caused by interaction of the incident wave with the rigid structure. Although the relative magnitude of the reflected pressure can vary slightly depending on the magnitude and angle of incidence of the free-field wave, the total pressure on the incident surface is generally about twice the free-field value. Thus, the final expression for the axial force on the propeller as a function of time is:

$$F(t) = 2\int_{-1}^{3}\int_{0}^{2\pi} Pm[\exp(-Tr/\theta)]R\,d\phi\,dR \qquad (2.3)$$

Numerical integration of equation 2.3 can be readily accomplished once a relationship between peak pressure and standoff distance is established to provide values of Pm.

B. RESPONSE OF THE SHAFT

As shown in Figure 2.2, the shaft is to be modeled as a fixed-free bar, with motion restricted to one dimension. The connection between the shaft and the main engine is considered rigid in the horizontal direction, where the shaft collar has been jacked back against the aft thrust

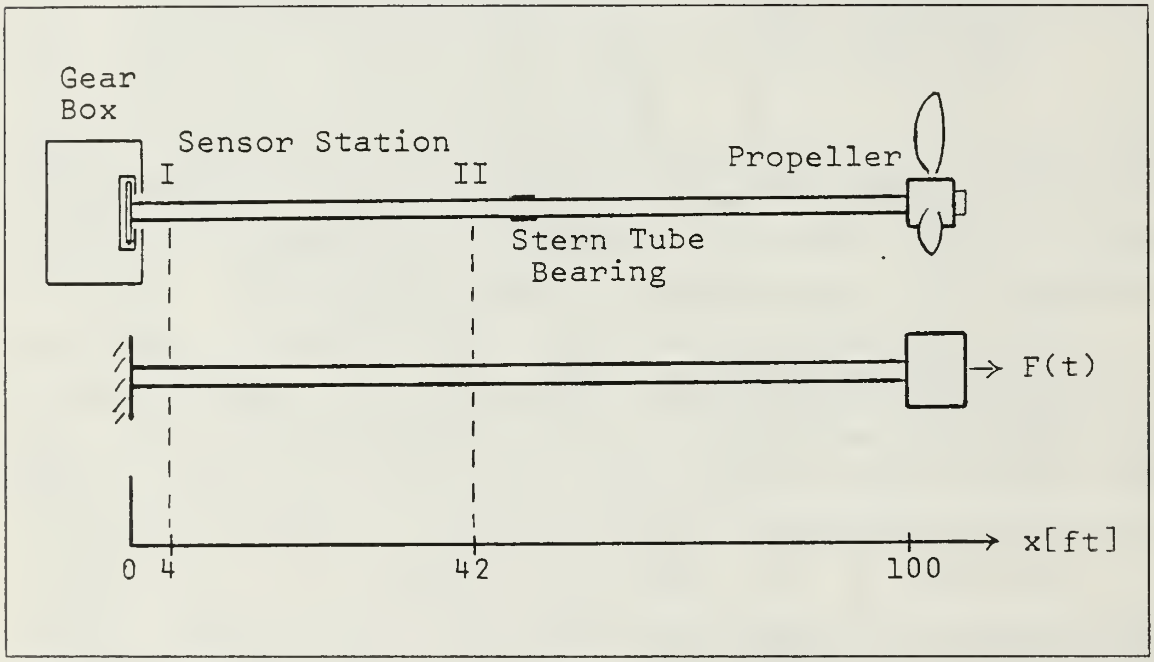


Figure 2.2 Propulsion Shaft Model (USCGC CAMPBELL).

bearing shoes in accordance with [Ref. 2]. The effects of system damping are negligible with shock loading; hence, these will not be considered. The shaft is assumed to be continuous and of constant cross-section, although a slight approximation is made here in the case of CAMPBELL.

Since the shaft is considered to be a multi-degree-of-freedom system, the displacement of the shaft in the x-direction will be analyzed as a continuous wave. The equation of motion for axial vibration of a bar of constant properties (a good assumption in this case) is:

$$\ddot{u} - a^2 u'' = 0 \qquad (2.4)$$

where $u(x,t)$ is shaft particle displacement, and is a function of both time and position along the shaft. The wave propagation velocity "a" is about 200 inches per msec for steel. The general solution to equation 2.4 is:

$$u(x,t) = f(x - at) + g(x + at) \qquad (2.5)$$

For the case of a single wave traveling in the -x direction in Figure 2.2, this reduces to:

$$u(x,t) = g(x + at) \qquad (2.6)$$

The longitudinal strain in the shaft is defined as the partial derivative of $u(x,t)$ with respect to the axial coordinate x:

$$e(x,t) = g'(x + at) \qquad (2.7)$$

The shaft particle velocity is similarly defined by taking the partial derivative of $u(x,t)$ with respect to time:

$$v(x,t) = a\dot{g}(x + at) \qquad (2.8)$$

Since the strain wave is undistorted as it moves down the shaft with velocity "a", it can be shown [Ref. 8] that g' is equal to $\dot{g}$. Therefore:

$$v(x,t) = ae(x,t) \qquad (2.9)$$

Integrating both sides of equation 2.9 with respect to time provides a relationship between shaft displacement and longitudinal strain:

$$u(x,t) = a\int_0^t e(x,t)dt \qquad (2.10)$$

This relation is valid at any point along the shaft except very close to the fixed end, where the displacement is always theoretically zero.

The strain e(x,t) is a relatively simple quantity to measure experimentally. Alternatively, however, it can be evaluated by observing the following from static strength analysis:

$$e(static) = F/[EA] \qquad (2.11)$$

Here, F is the axial force expressed by equation 2.3 for a particular time t. Equation 2.11 is only valid, however, if the force is applied slowly. For impulsive loads, the response is not the same. It is the maximum response that is of interest, and for a short duration impulse, this occurs after the load has been applied (during the free-vibration phase). A dynamic magnification factor D must be determined from the response spectrum for the particular impulse experienced [Ref. 9]. The final equation for the peak strain is:

$$e(max) = D[F(max)]/[EA] \qquad (2.12)$$

Thus, an approximation for the maximum shaft displacement can be arrived at in two ways. The strain wave can be measured directly, or the forcing function defined by equation 2.3, based on experimental shock wave pressure data, can be used to solve equation 2.12. Both should give similar results, which can then be used to solve equation 2.10 for the displacement of the shaft.

III. FIELD EXPERIMENT

A. TEST PLATFORM

The test platform, ex-USCGC CAMPBELL (WHEC-32), was inspected both underwater and within at its berth at Naval Station, San Diego, California, and was found to represent an excellent model for the planned experiment. Original ship drawings were obtained to determine as precisely as possible such parameters as shaft length, propeller weight, etc. The services of Mobile Diving and Salvage Unit ONE Detachment were enlisted for diving, logistics, and explosive handling support. The experiment was conducted during the period 25-29 June 1984.

The CAMPBELL-class high endurance cutters are equipped with Westinghouse geared turbines rated at 6200 SHP on two shafts of about 103 feet in length. Their dimensions are 327 feet LOA, mean draft of 15 feet, and a standard displacement in excess of 2200 tons. CAMPBELL was chosen as a test platform primarily because of its availability, but additionally because its dimensions and layout are roughly proportional to a small combatant's.

B. OBJECTIVES OF THE EXPERIMENT

The objectives of the experiment were to obtain the following information:

(1) Free-field pressure measurements for 50 grain-per-foot detonating cord to be used in later numerical modeling.

(2) Strain wave data for two points on the shaft. These are labeled Stations I and II in Figure 2.2, and correspond to the locations of the

reduction gears and stern tube seal.

(3) Shaft acceleration data near the gear box.

The free-field pressure data would provide values of Pm in equation 2.3 to be used as input for numerical modeling. The strain gages would provide direct measurement of the strain wave as defined by equation 2.7. Finally, the accelerometers would provide a direct measurement of the maximum acceleration of the shaft, $\ddot{u}(max)$, near the main engine.

C. EXPERIMENTAL APPARATUS

All data was captured with a Honeywell M101 Wideband II (direct record) tape recorder using a recording speed of 120 inches-per-second, providing a frequency band-width capability of 500 kHz. Additionally, on-site verification of test results was provided by a Honeywell 1508B Visicorder.

Two types of piezoelectric pressure transducers were utilized for this experiment. Three PCB (Piezotronics, Inc.) 138A50 pressure sensors with built-in line driver amplifiers and six NSWC (Naval Surface Weapons Center) pressure sensors without in-line amplifiers were utilized. Both transducer types feature a volumetric-sensitive tourmaline crystal element suspended in an insulating oil. As discussed in [Ref. 6], tourmaline crystals are ideally suited for underwater explosion pressure measurements. Their ability to sense changes in hydrostatic pressure gives these gages a 3-dimensional character which allows them to respond equally to blast waves from any direction.

The strain gages used at Stations I and II were BLH Electronics (SR-4 brand) FAE-25-35, 350 ohm, constantan foil strain gages. Finally, two accelerometers, including a PCB 302A model with a 500-g range, were positioned at Station I near the gear box. The accelerometers were glued to the shaft with Devcon Corporation "Plastic Steel" No. 10240.

D. EXPERIMENTAL PROCEDURE

A total of 14 shots were conducted during the five day period of the experiment; they will be referred to by the order in which they were performed. Eight of these were so-called free-field pressure shots in which the propeller and shaft were not subjected to a shock loading. The remaining six shots comprised the actual shock tests.

1. Preliminary Testing (Shots 1-4)

The first four shots were free-field tests conducted for the purpose of checking out the electronics and for determining a proper standoff for the pressure transducers. Three "wraps", or turns, of detcord were placed spirally directly on the shaft at a location remote from the propeller and bearings. The pressure transducers were placed in the free field, at the same depth as and outboard of the shaft. The first shot at nine feet registered no pressure rise on any of the transducers. The second shot at two feet registered a peak value of approximately 2000 psi. The third and fourth shots brought the range to within inches, registering peak pressures on the order of 20,000 and 40,000 psi, respectively.

These first four shots demonstrated several things. First, the transducers would have to be very close to the charge to record any significant pressures. This fact would eventually lead to the decision to forego taking pressure measurements during actual shock testing. The close proximity of the transducers to the ringing effects of the propeller hub, shaft, and strut bearing would have rendered the data so-obtained largely unreadable.

Second, their was excellent correlation between the PCB and NSWC transducers, lending credibility to future readings. Although both types are built around tourmaline

Figure 3.1 Data Acquisition Electronics Package.

crystals, their physical construction is quite different. The substantially more rugged design of the NSWC transducers lead to their exclusive use in later tests after two of the PCB sensors were damaged during a shot.

All signal amplifying and recording equipment was operated from the back of a van (Figure 3.1) by NPS electronics technician Tom Christian, where it was kept out of the direct sunlight and cooled by the ocean breeze. The third point which these first four shots demonstrated was the excellent performance of the Honeywell M101 tape recorder, which was verified on-site with the Honeywell 1508B Visicorder.

Finally, it was observed that, although the outer fiberglass shaft coating was removed wherever the detcord had been in contact with it prior to each shot, the shaft steel itself showed no visible signs of scoring or other

damage. Later free field shots performed with the detcord wound on top of a one-inch layer of manila line, and with charges as large as five wraps, caused no visible damage to the fiberglass shaft coating.

2. Shock Testing (Shots 5-10)

Upon completion of the four preliminary free-field shots, enough information had been obtained to commence the actual shock testing. The shaft was carefully inspected both underwater and inside the ship to ensure that it was, in fact, in a fixed-free condition as shown in figure 2.2. Weld restraints installed to prevent the propeller from windmilling during towing were removed, so that the only fixed point in the one-dimensional analysis being undertaken was the gear box end of the shaft. The propeller dunce cap and rope guards had been removed previously. All sensors were placed in position. In all respects, the port propeller was ready for removal using the detcord method discussed in [Ref. 2], with one exception: the propeller hub boss nut was not backed off at all. The reason for this was two-fold. First, once the propeller had broken free of the static friction generated by its original installation tight around the shaft, this initial condition would have been lost for subsequent shots. Second, by restraining the propeller on the shaft and thus making them an integral unit, none of the energy from the detcord detonation imparted to the propeller hub would be lost either through heat generated by dynamic friction between hub and shaft, or through momentum transfer between the propeller blades and the water. Thus, a worst-case situation with respect to the total impulse imparted to the shaft was made available for each shock test.

According to [Ref. 2], the size of the detcord charge in actual practice is to be limited to four wraps.

This rule of thumb is true regardless of the shaft diameter. It was decided, therefore, to subject CAMPBELL's shaft to shock loadings from one-, three-, and five-wrap charges.

The first two shock tests, shots 5 and 6, were essentially the same test conducted twice. One wrap of detonating cord was used for each of these two shots. As in all the shock tests, the detcord was wound on top of a one inch layer of manila line, thus separating it from direct contact with the shaft sleeve..

Three wraps of detcord were used for shots 7 and 8. For shot 7, the detcord was wrapped spirally, as is probably done in practice in most cases. For shot 8, however, it was wrapped concentrically against the propeller hub in accordance with [Ref. 2], and held in place with underwater epoxy. Unfortunately, it was later discovered that the data from shot 8 had been inadvertently erased by the recording of a later shot. However, the on-site Visicorder traces survived and were available for later analysis.

Shots 9 and 10 were similar to the previous two. This time five wraps of detcord were used. For shot 9, the detcord was wrapped spirally; for shot 10, concentrically against the hub.

3. Free-Field Testing (Shots 11-14)

When the first set of free-field shots described above were conducted, there was no data or experience base available to assist in determining an appropriate transducer standoff distance. After ten shots had been completed, this was no longer a problem, and a more precise method was devised for obtaining pressure-time histories within the range of interest for the last series of free-field tests. Three of the NSWC pressure transducers were arranged so that the standoff from the detcord was sequentially one, two, and three inches, respectively. The detcord was wrapped

spirally as in the preliminary testing, at a location where the ship's hull or appendages would not affect the early time pressure readings. This time, however, the detcord was wound on top of a layer of manila line to more accurately simulate conditions near the propeller hub. Shots 11 and 12 were with one wrap of detcord, shot 13 was with three wraps, and shot 14 was with five wraps.

This last series of free-field pressure measurements completed the experimental testing.

E. EXPERIMENTAL RESULTS

From the standpoint of quality data collection in the field, the experiment was considered a success. These tests were performed shortly after the first two in a series of experiments being conducted at NPS under sponsorship by the Defense Nuclear Agency to investigate the response of stiffened flat plates to underwater explosions of much greater magnitude. The hard lessons learned during these earlier experiments by other students were quite valuable to the present investigation.

Figure 3.2 illustrates the data collection flow-path for the experiment. All data was reviewed on-site using the Honeywell 1508B Visicorder. These records, such as the one shown in Figure 3.3, provided a means of partially verifying results in the field. Note that the relative distance between each pressure transducer can be determined by comparing the real time delay between pulses to the theoretical value of approximately 16.7 μsec. Upon return to NPS, data from all tests (except shot 8) was digitized and displayed on an HP-5451C Fourier Analyzer, using a real-time record step of 10 μseconds. After accounting for the 64-to-1 recording ratio of the Honeywell M101, this provided a digitized time step of 0.156 μsec. This is considerably

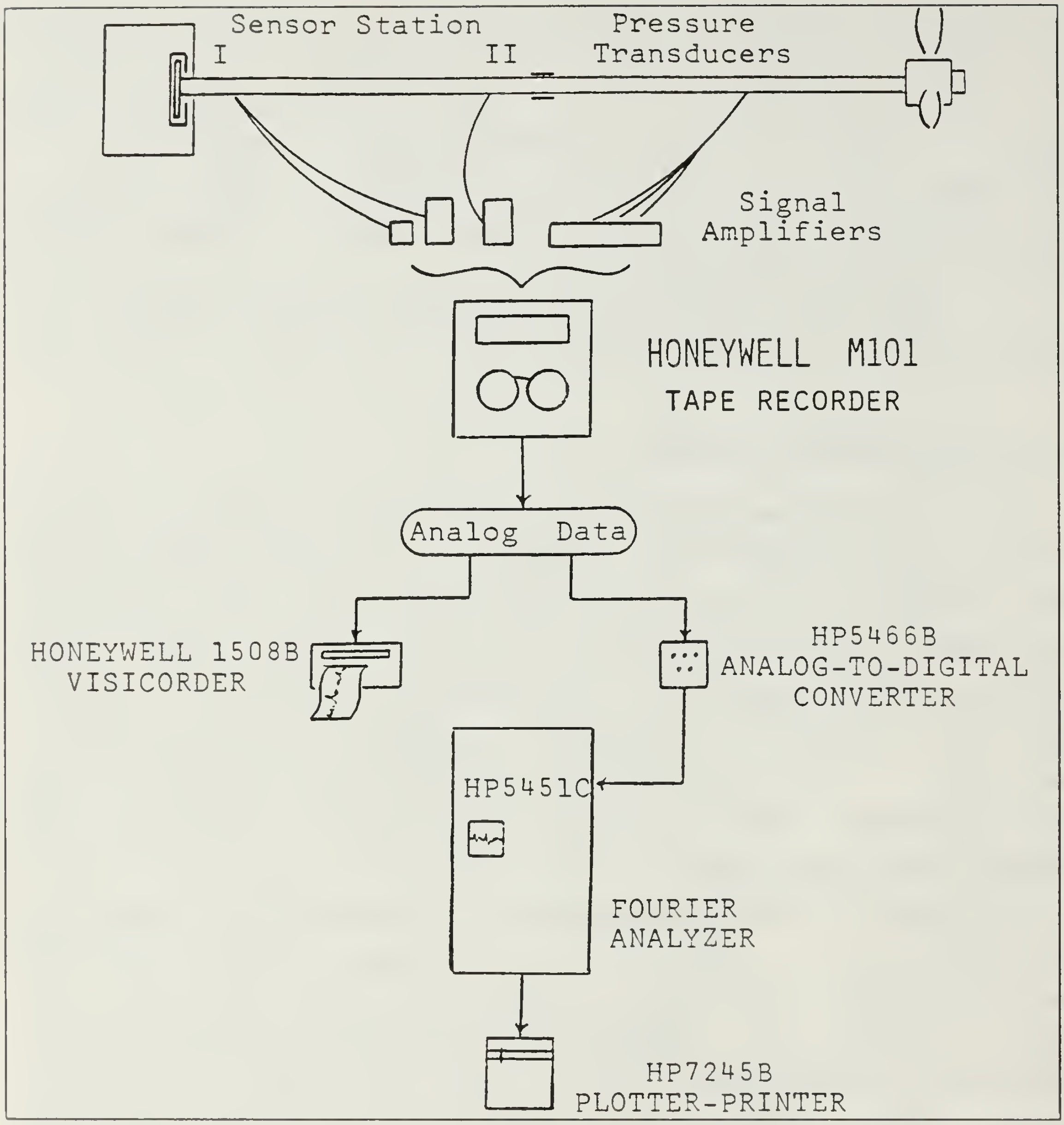


Figure 3.2 Data Acquisition Flow-path.

faster than the calibrated signal rise times, which were on the order of 4 to 6 μsec.

Digitized data output from the HP5451C is provided in Appendices A and B. The start-times indicated on each plot are relative to that sensor only. Also, the zero-magnitude

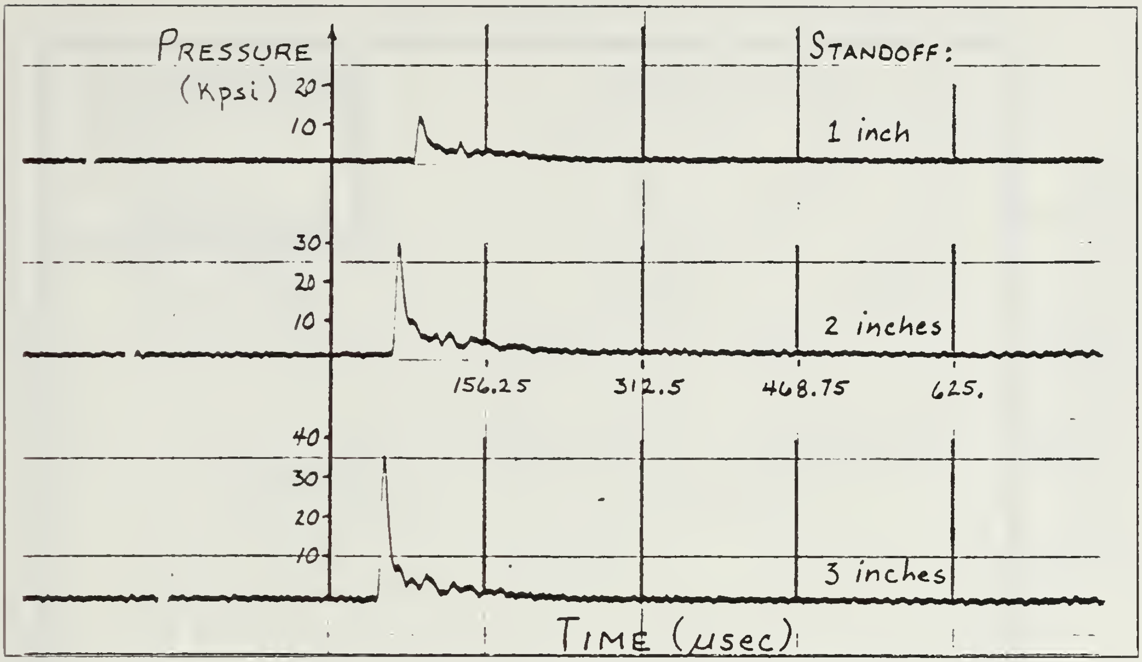


Figure 3.3 Pressure Profiles for a 5-wrap Charge.

levels were not always set precisely on zero. Therefore, adjustments were made as necessary based on the complete time history where peak values were required for analysis.

The complete pressure-time histories for shots 11 through 14 are recorded in Appendix A. They are of good quality, as compared to data from other underwater explosion tests. The primary reason for this appears to be the Honeywell M101's ability to record the events at such a high speed, while maintaining an acceptable signal-to-noise ratio.

Figure 3.4 illustrates the relationship between peak pressure and standoff distance for a given charge size. The recorded pressures were adjusted slightly to account for the gage response of the transducers [Ref. 10]. This data would provide the basis for later numerical prediction discussed in Chapter IV. The pressure-time histories in Appendix A display a near-constant rise time of about four μsec, which is approximately the limit of the instrumentation.

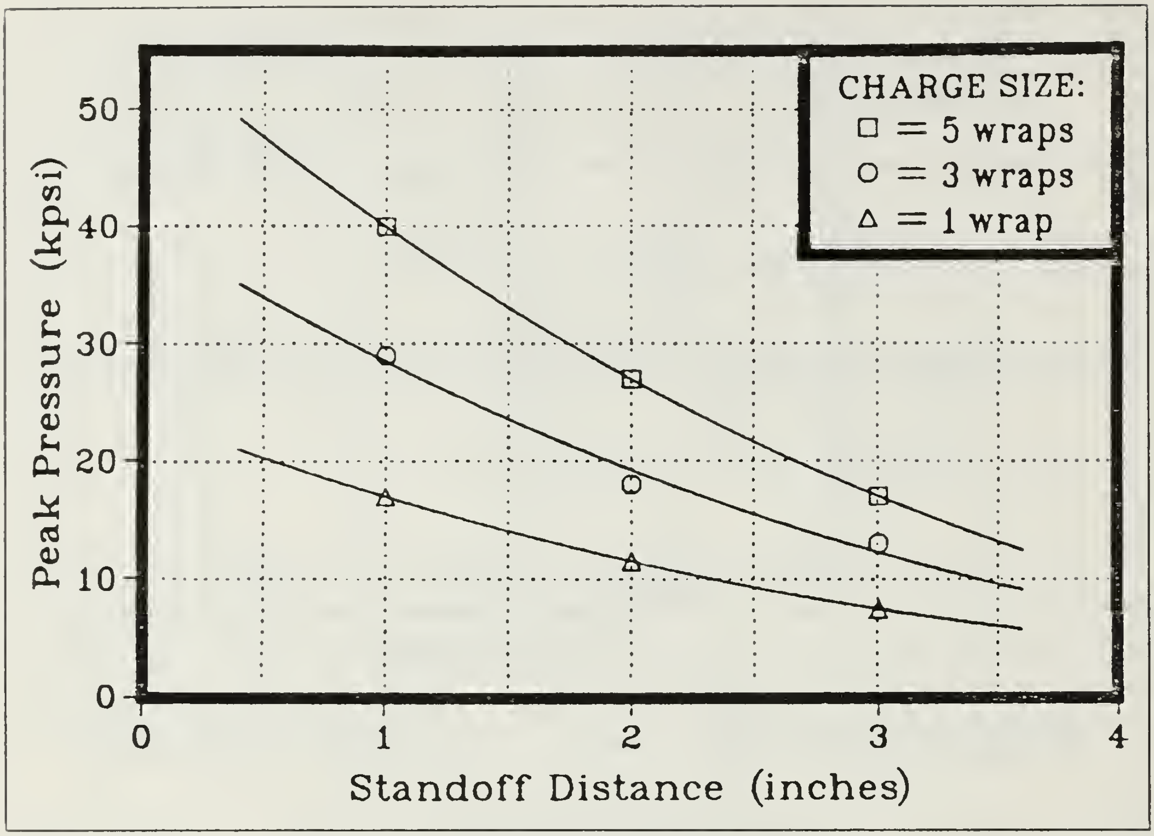


Figure 3.4 Peak Pressure vs. Standoff Distance.

The maximum strain for each shot is summarized in Figure 3.5, and plotted as a function of charge size in Figure 3.6. As expected, the strains at each station are about constant for any particular shot. Note, however, that the peak strain is apparently unaffected by whether the detcord was wrapped spirally or concentrically around the shaft. The total strain wave for each shot, shown in Appendix B, also shows little change in form for a given charge size, regardless of the arrangement of the detcord. Finally, peak accelerations at Station I increased linearly with charge size within the range of the experiment, as shown in Figure 3.7.

NO. of WRAPS	MAXIMUM STRAIN (μs) (Station I)	(Station II)
1	50	50
3 (spiral)	100	110
3 (concentric)	100	110
5 (spiral)	140	140
5 (concentric)	140	140

Figure 3.5 Summary of Maximum Strains.

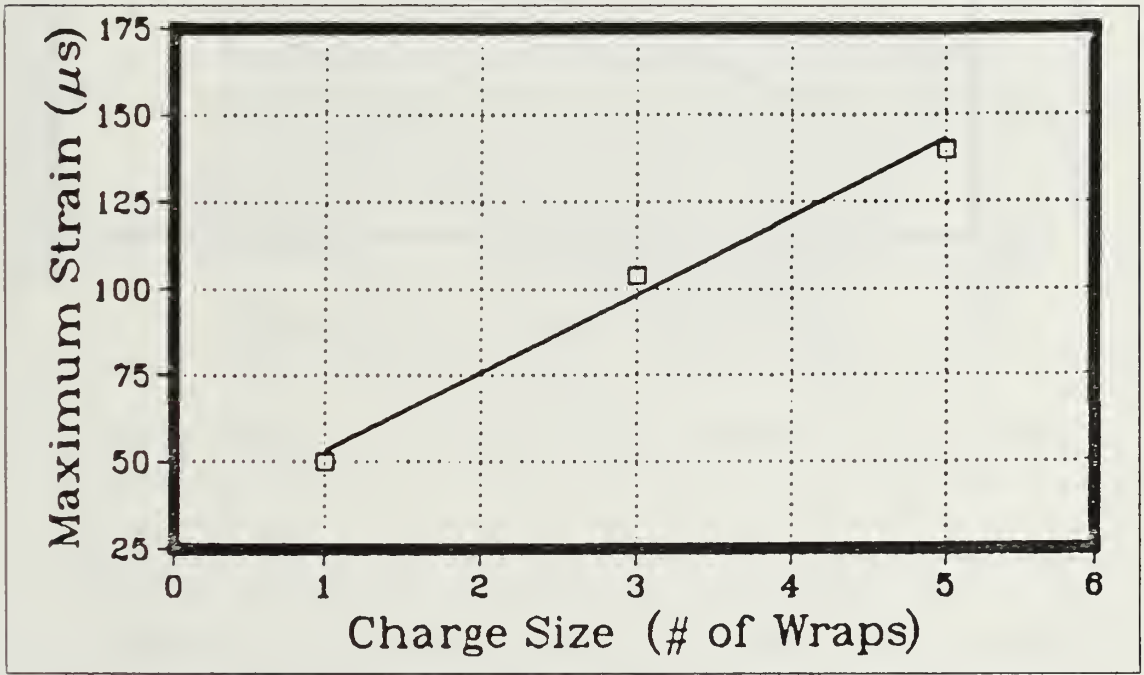


Figure 3.6 Maximum Strain vs. Charge Size.

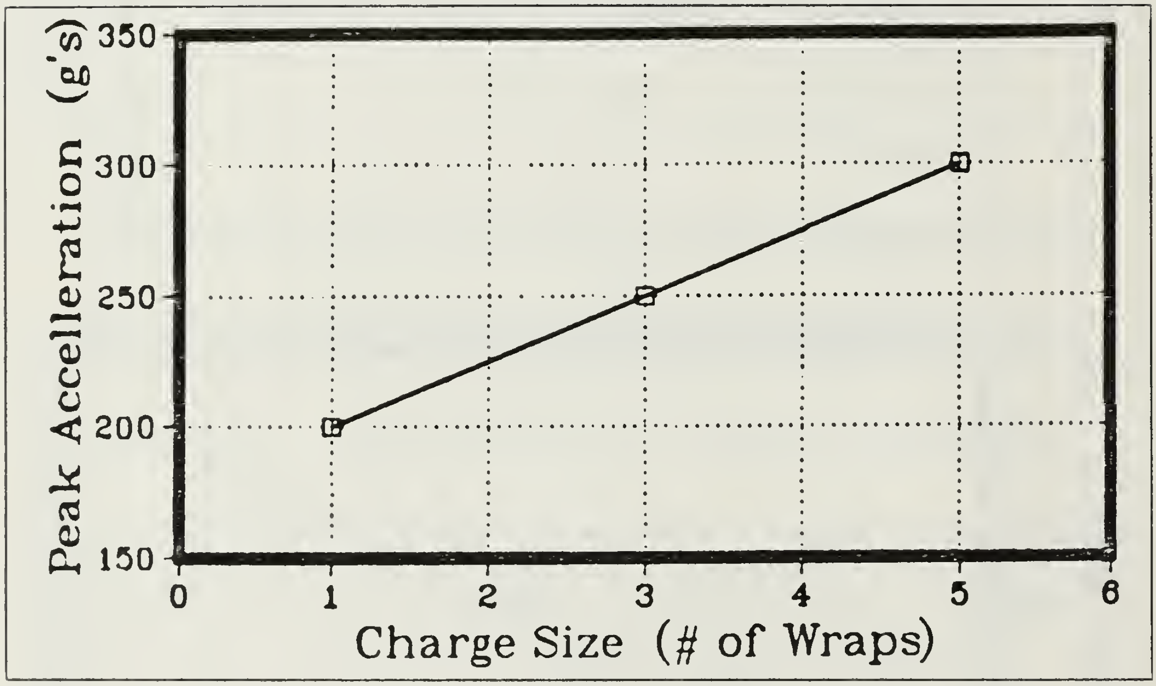


Figure 3.7 Maximum Acceleration vs. Charge Size.

IV. NUMERICAL PREDICTION USING EXPERIMENTAL RESULTS

A. DEVELOPMENT OF A NUMERICAL MODEL

The experimental pressure data collected on the CAMPBELL tests was to be used as the basis for the impulsive loading input to a numerical scheme for predicting shaft response from an underwater detcord blast. A snapshot of this loading as a function of both time and standoff is illustrated in Figure 4.1 for a 3-wrap charge.

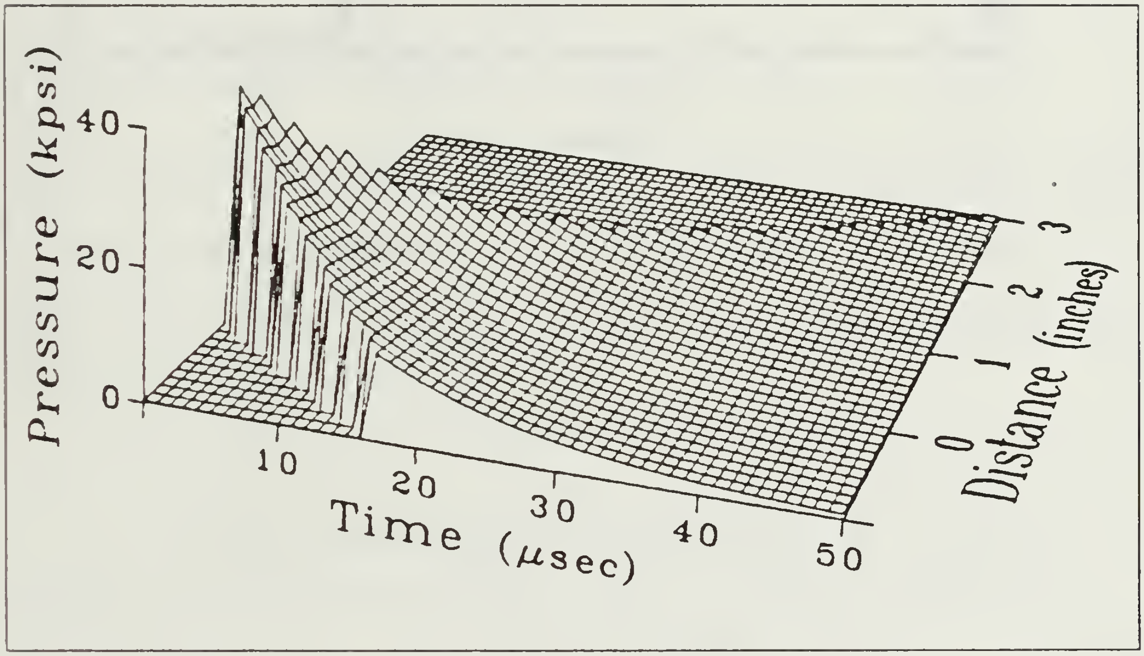


Figure 4.1 Unit Impulse Based on Experimental Results.

A FORTRAN program was written to arrive at a numerical equivalent to the axial shaft force defined by equation 2.3 (see Appendix C). Values for Pm were obtained from the relationship between peak pressure and standoff distance

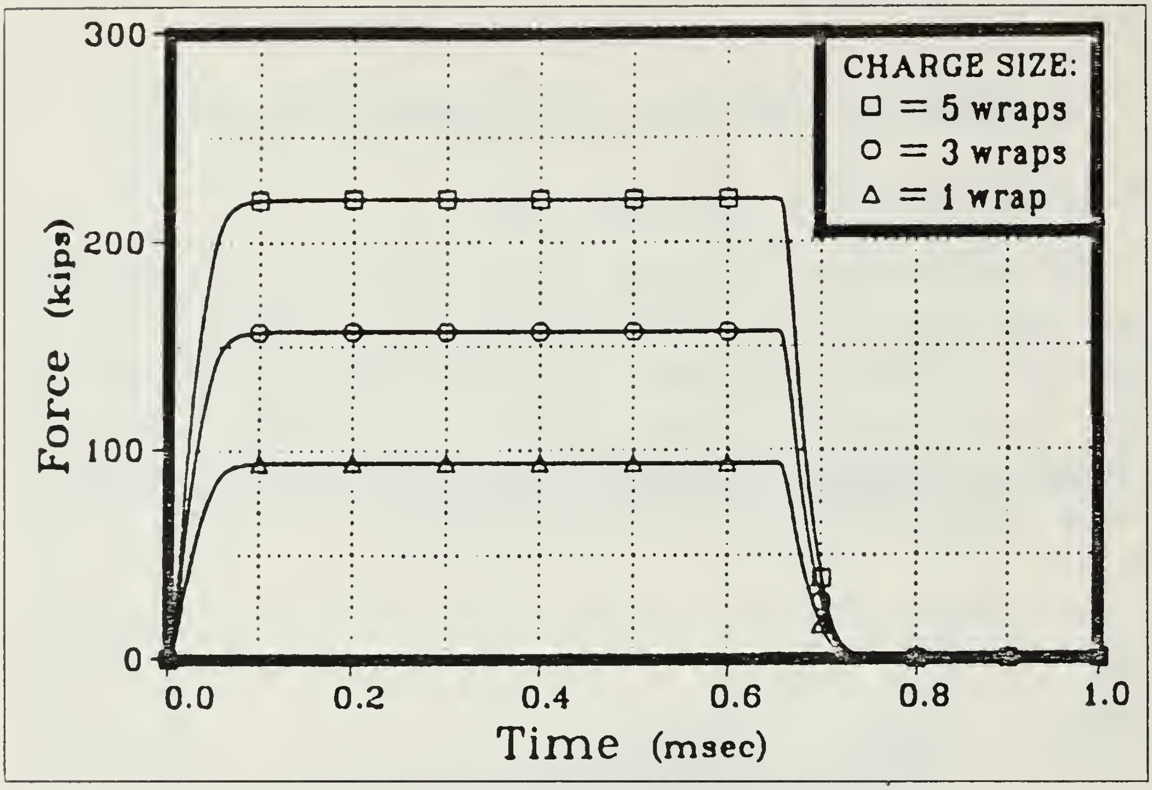


Figure 4.2 Force Applied to CAMPBELL's Shaft.

illustrated in Figure 3.4. The results are shown in Figure 4.2.

B. COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

A good approximation of the forcing function illustrated in Figure 4.2 is a rectangular impulse. For this type of loading, [Ref. 9] defines the dynamic magnification factor as

$$D = 2\sin[\pi(B)] \tag{4.1}$$

where B is the ratio of the load period to the period T at which the shaft responds. From Figure 4.2, the load period

is 0.7 msec. The strain wave histories in Appendix B indicate that the half period of shaft response corresponding to the lowest excited frequency is around 2 msec (i.e., T is in the vicinity of 4 msec). It can be shown [Ref. 12] that the natural frequency of the shaft-propeller system can be expressed:

$$(2\pi fL/a)\tan(2\pi fL/a) = Ms/Mp \qquad (4.2)$$

where

- f = natural frequency
- L = shaft length
- a = speed of sound in the shaft material
- Ms = total mass of the shaft
- Mp = mass of the propeller and boss nut

Solving equation 4.2 for the natural frequency in the region of interest for CAMPBELL yields a value of 270 Hz. This corresponds to a natural period of 3.7 msec. These results were verified on the HP5451C Fourier Analyzer. Inserting this result into equation 4.1 yields a dynamic magnification factor D of approximately 1.12.

Each of the strain profiles in Appendix B can be approximated analytically as a sine wave whose magnitude varies according to charge size. With this knowledge, equation 2.9 can be redefined accordingly for any fixed location on the shaft:

$$v(t) = ae(max)\sin[2\pi t/T] \qquad (4.3)$$

Similarly, for any given value of x (except right at the gear box), equation 2.10 can be expressed:

$$\begin{aligned} u(t) &= ae(max)\int_0^t \sin[2\pi t/T]dt \qquad (4.4) \\ &= -[T/2\pi]ae(max)\cos[2\pi t/T] \end{aligned}$$

Finally, the expression for the maximum displacement of the shaft is simply:

$$u(max) = [T/2\pi]ae(max) \qquad (4.5)$$

As indicated in Chapter II, values of e(max) used in equation 4.5 can be obtained experimentally by direct strain gage measurement, or numerically through the use of equation

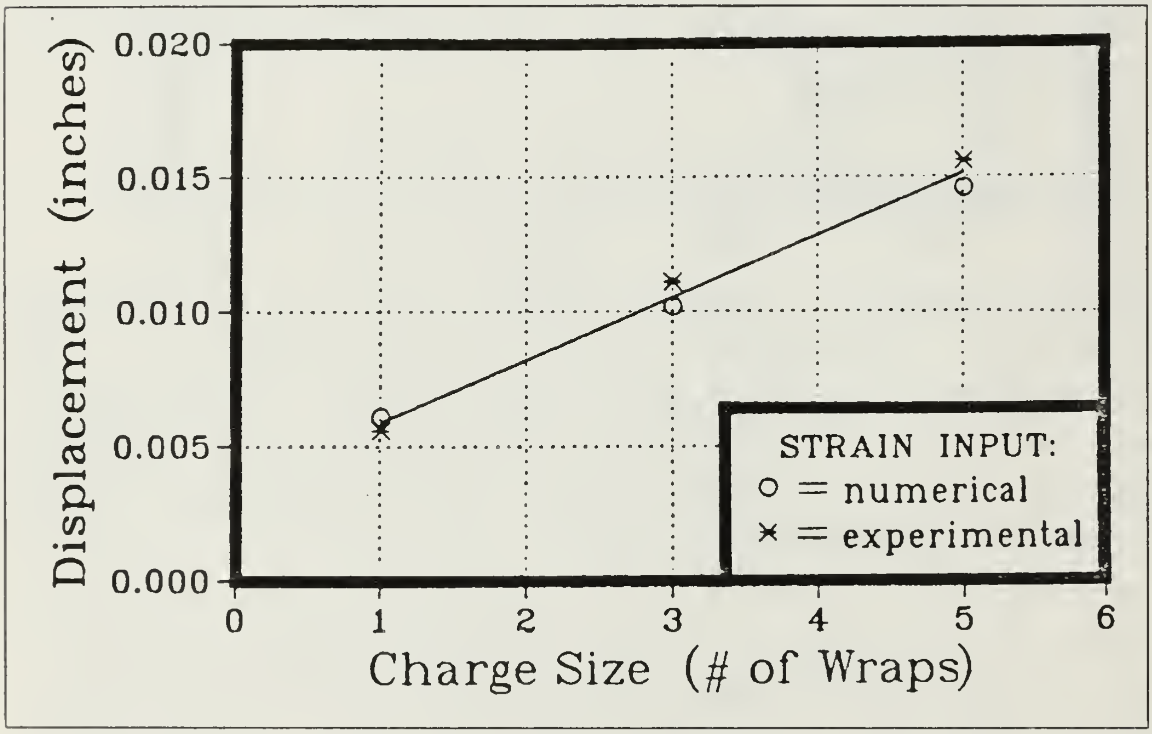


Figure 4.3 CAMPBELL Shaft Displacement vs. Charge Size.

2.12. Figure 4.3 summarizes the results obtained for maximum shaft displacement for both methods. The numerically determined values display a linear relationship with increasing charge size that is adequately approximated by the experimental record within the range observed, supporting the assertion that the numerical model is an acceptable one for further prediction purposes.

C. NUMERICAL ANALYSIS OF DDG-2 SHAFT CONFIGURATION

Having established the validity of a method for predicting the response profile of the shaft in the case of CAMPBELL, a specific in-service shaft configuration will now be analyzed. The USS CHARLES F. ADAMS (DDG-2) class of guided-missile destroyers was chosen for this purpose. Experience among U. S. Navy diving supervisors indicates this large class of surface combatants is one of the most frequent candidates for waterborne propeller replacement. Additionally, recent ship systems upgrades for this class indicate that many of these ships will continue to serve with the fleet for several years ahead.

MODE #	NATURAL PERIOD (msec)	
	CAMPBELL	CHARLES F. ADAMS
1	27.6	31.1
2	9.1	9.8
3	5.4	5.6
4	3.7	3.8
5	2.9	2.9
6	2.3	2.4
7	2.0	2.0

Figure 4.4 Natural Shaft Periods for Both Ships.

Shaft blueprints for the ADAMS class were obtained from the planning yard. It was decided to analyze the port shaft, since it more closely resembled the configuration on CAMPBELL. Values for the first seven natural periods of longitudinal vibration for the port shaft were computed using equation 4.2 and the shaft geometry defined by the

blueprints. These were compared with equivalent values obtained for CAMPBELL as shown in Figure 4.4. For higher frequencies in the region of interest, the natural periods of both shaft configurations actually converge, giving indication of a similar response profile for a given shock loading. It is reasonable to expect, therefore, that ADAMS' port shaft would be excited primarily at the fourth natural period, as was the case with CAMPBELL.

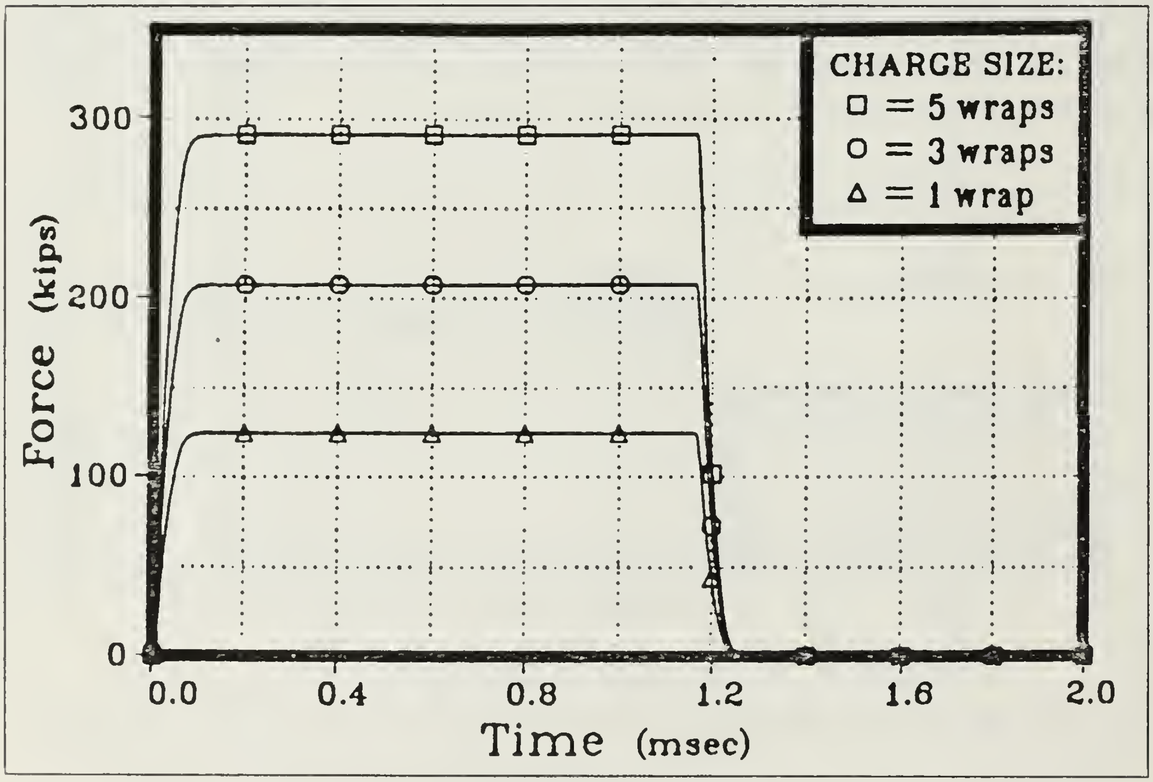


Figure 4.5 Predicted Force on ADAMS Shaft.

Given the larger shaft diameter of the ADAMS class over CAMPBELL, the length of each wrap of detcord would be increased proportionally. Taking this into account, as well as the larger surface area of the propeller hub over which to carry the integration, the force which would be applied

to the end of ADAMS' port shaft was predicted as was done for CAMPBELL, and the results are shown in Figure 4.5. As expected, the shape of the loading is nearly identical to that experienced on CAMPBELL. The period of the load, however, would be 1.2 msec. Observing from Figure 4.4 that the natural period of interest is T = 3.8 msec, equation 4.1 provides a dynamic magnification factor of 1.67. Utilizing equation 2.12 to obtain the maximum theoretical strains that would be experienced for a given charge size, the equivalent shaft displacements can be predicted using equation 4.5. These are plotted for the port shaft of USS CHARLES F. ADAMS (DDG-2) in Figure 4.6.

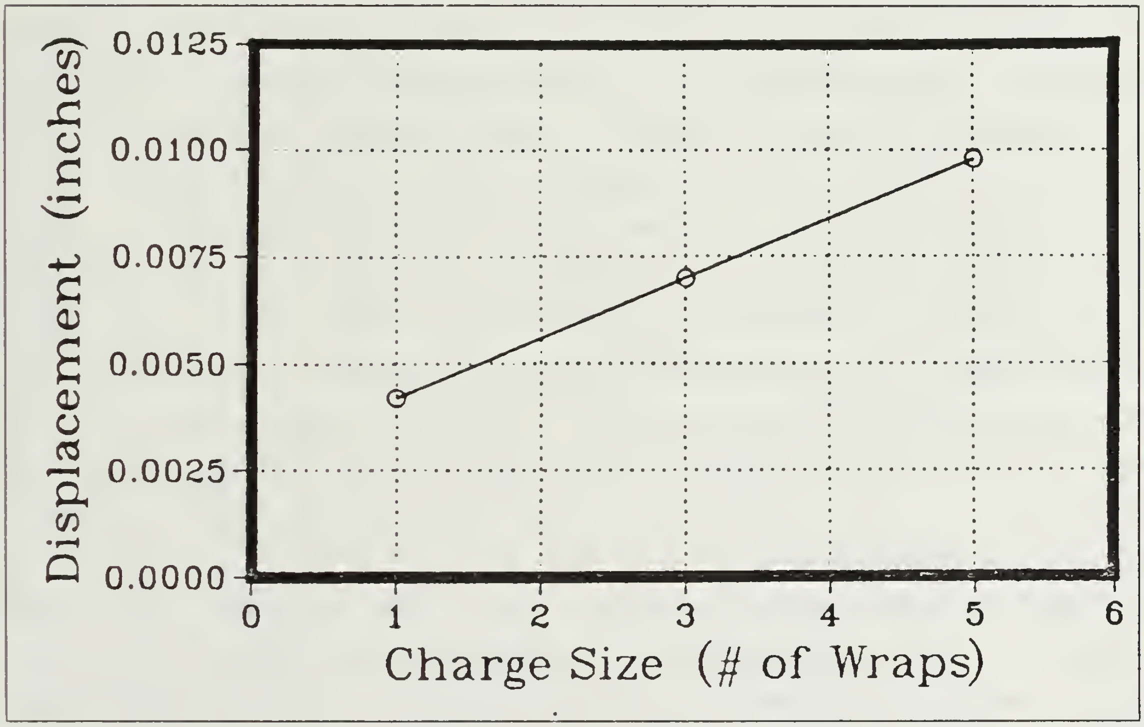


Figure 4.6 Predicted Shaft Displacement for ADAMS.

V. CONCLUSIONS AND RECOMMENDATIONS

A. RESULTS OF THE INVESTIGATION

According to [Ref. 2], the maximum static removal force to be used in unseating the propeller from an ADAMS-class destroyer is 400 tons (800 kips). From Figure 4.5, the maximum predicted force from a 5-wrap charge is 145 tons (290 kips). Multiplying this value by the dynamic magnification factor of 1.67 calculated for ADAMS, an equivalent force of 240 tons is obtained, leaving a considerable margin of safety under this criterion.

Although Figure 2.2 indicates a zero displacement condition for the shaft collar at the thrust bearing, this is only true for tensile loads. The initial tensile wave in the -x direction will be reflected as another tensile wave in the +x direction. Upon arrival at the propeller, the strain wave will be reflected again in the -x direction, but this time as a wave of compression. By the time this compressive wave reaches the thrust bearing, it will be on its third trip along the shaft, and some dissipation of its magnitude is to be expected. However, as a conservative estimate, it is assumed that this wave arrives at the gear box undiminished.

The DDG-2 reduction gear technical manual [Ref. 13] defines a minimum allowable endplay on the shaft collar/ thrust bearing interface of 0.019 inches. This is twice the displacement predicted for ADAMS from a 5-wrap detcord charge in Figure 4.6, a prediction that includes several conservative assumptions which realistically should provide for an even greater safety margin. This means that the shaft collar will not compress the forward bearing shoes

sufficiently to transfer the shock loading indicated in Figure 3.7 to the reduction gears. It is therefore concluded that, at least within the range of charge sizes tested, the use of detonating cord to remove a propeller from an ADAMS-class destroyer will result in no detrimental effects on the thrust bearing or the reduction gears. Given the extremely small magnitude of expected shaft displacement, it is also concluded that friction damage to strut, stern tube, or line shaft bearings, or to the stern tube seal itself, would be non-existent to any measurable degree.

B. RECOMMENDED PROCEDURAL REVISIONS

Due to limitations in funding, it was not possible to obtain information regarding the theoretical charge size required to loosen the propeller for a given shaft configuration. The number of wraps required in any particular case will be primarily a function of propeller weight and the size of the shaft/hub contact area. Realistically, it should not be fixed at a certain value as suggested by [Ref. 2]. Model testing would have reduced the problem to a minimum number of variables, and allowed selective introduction of secondary factors such as variable installation force and surface corrosion of the contact area. Experience in the fleet on this subject would provide a suitable substitute for more precise methods of determining a rule of thumb for charge size. As the use of detonating cord has been discouraged in recent years, however, much of this experience will soon be lost unless it is tapped soon.

Based on observations mentioned in Chapter III, it is recommended that the detcord be wrapped as close to the shaft as possible, with perhaps a minimum standoff of one inch as used in this series of tests. Damage to the outer shaft sleeve and fiberglass coating at this range was found

to be nonexistent. Furthermore, reducing the standoff limits the bending moment produced by asymmetrical loading which results from the finite detonation velocity of detcord. A large standoff may cause the aft inside circumference of the hub to bind on the shaft, and may be the reason that multiple shots are occasionally required to loosen the propeller from the shaft taper. Diving supervisors should take care, however, to ensure that the detcord is not placed in direct contact with sharp corners in the face of the propeller hub, such as near the gland.

It was also observed in Chapter III that the shaft response was apparently uneffected by the arrangement of the detcord (i.e., spiral vs. concentric). The procedure described in [Ref. 2] specifies concentric wrapping. Although this looks nice on paper, it is apparently not worth the effort. The detcord should simply be wrapped as close to the hub as convenience allows and in such a manner as to ensure that it remains in place.

Another superfluous exercise commonly practiced is the "tamping" of the detcord charge with line in an apparent effort to direct the energy of the explosion towards the hub. The concept of tamping is based on a significant differential in the densities of the tamping material and the surrounding medium. For example, explosives are used extensively in mining and road building to break up rock for ease in removal. A narrow hole is drilled in the rock, the explosive charge placed inside, and the hole is filled with dirt to contain the explosion and prevent premature venting. In this case, the dirt is obviously much heavier than the surrounding atmosphere, and effectively "tamps" the explosive charge. In the case of an underwater detcord explosion, however, the density of any surrounding line is at best equivalent to the density of the water, and there is thus no advantage to wrapping the detcord charge with line.

Even more significant, water is nearly incompressible, and thus the surrounding medium alone, in this case, effectively tamps the charge against the hub.

Past experience indicates that electric blasting caps are generally used when employing detcord in the field. Formal Navy (non-EOD) diver training in explosives is infrequent and often not commensurate with the hazards involved in handling these sensitive initiators, especially in the vicinity of large numbers of ships where stray currents abound. The reluctance to use non-electric blasting caps appears to be founded in the idea that there is a loss of control over the precise moment of detonation. During the 14 shots conducted as part of this investigation, non-electric caps were used exclusively to evaluate their performance and the degree to which the time of detonation could be estimated. In no case did the cap fail to detonate, nor did the actual time of detonation deviate from the estimated time (based on a preliminary time fuse test burn) by more that ten seconds. Given the fact that the area would have been cleared of all nonessential personnel regardless of the type of initiator used, this margin was considered quite satisfactory.

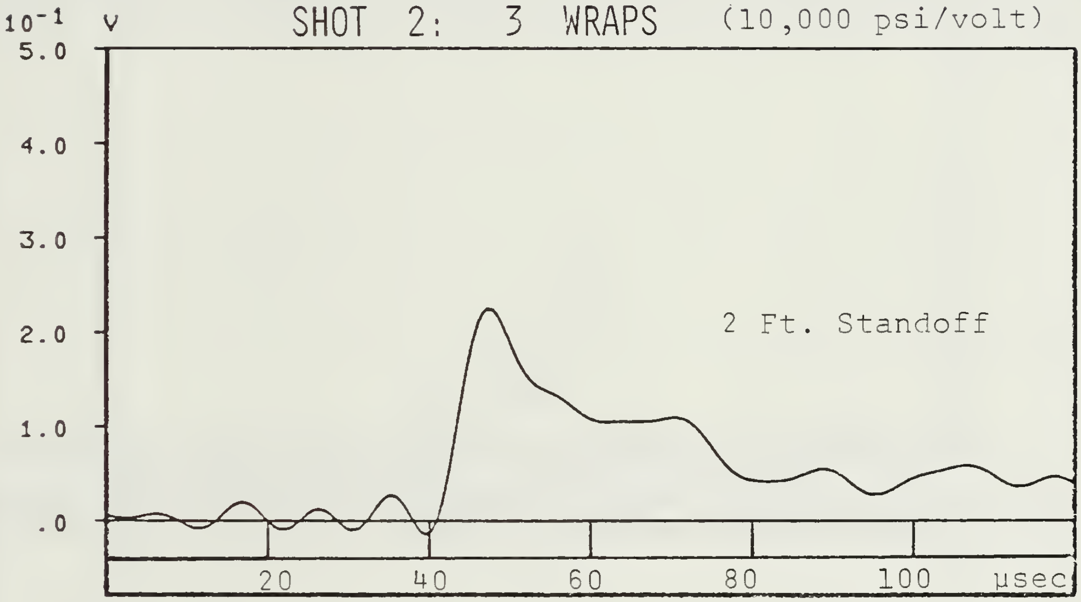
C. FINAL OBSERVATION

In light of the obvious cost savings, the use of Navy divers to perform an increasing number of underwater maintenance and repair tasks in the future appears certain. Nevertheless, frequent objections have been raised against the conduct of underwater ship husbandry in general, and against the use of explosives to remove conventional propellers in particular. In both cases, the underlying problem has not been the methods themselves so much as the lack of quality control. The few specific instances where damage

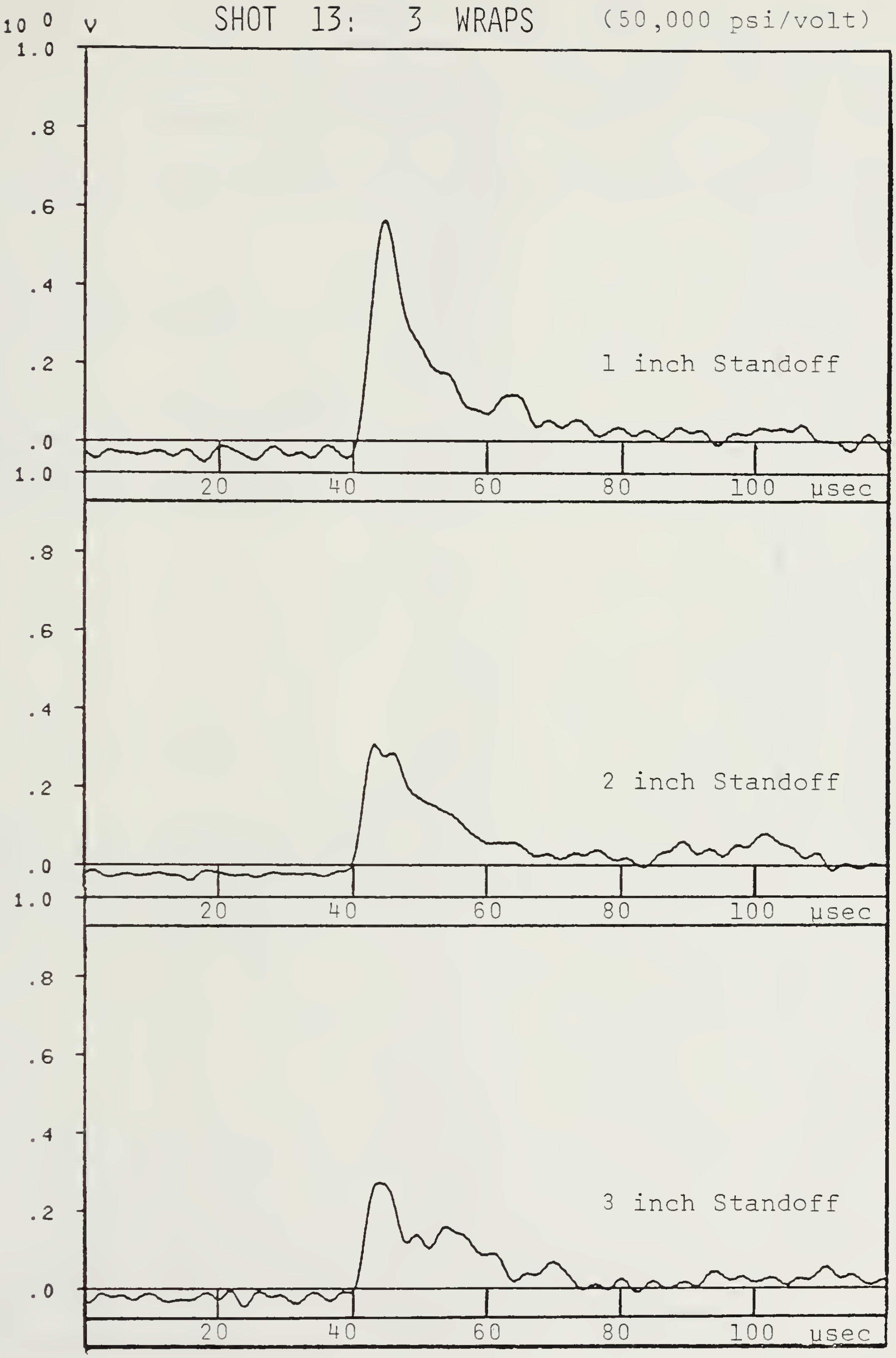
has resulted from using detcord in waterborne propeller replacement can each be attributed to a failure to follow established procedures and common sense. Where these procedures are followed, including the recommendations put forth herein, the use of detonating cord to remove a damaged propeller is considered a safe and viable alternative to other more costly and time consuming methods.

APPENDIX A

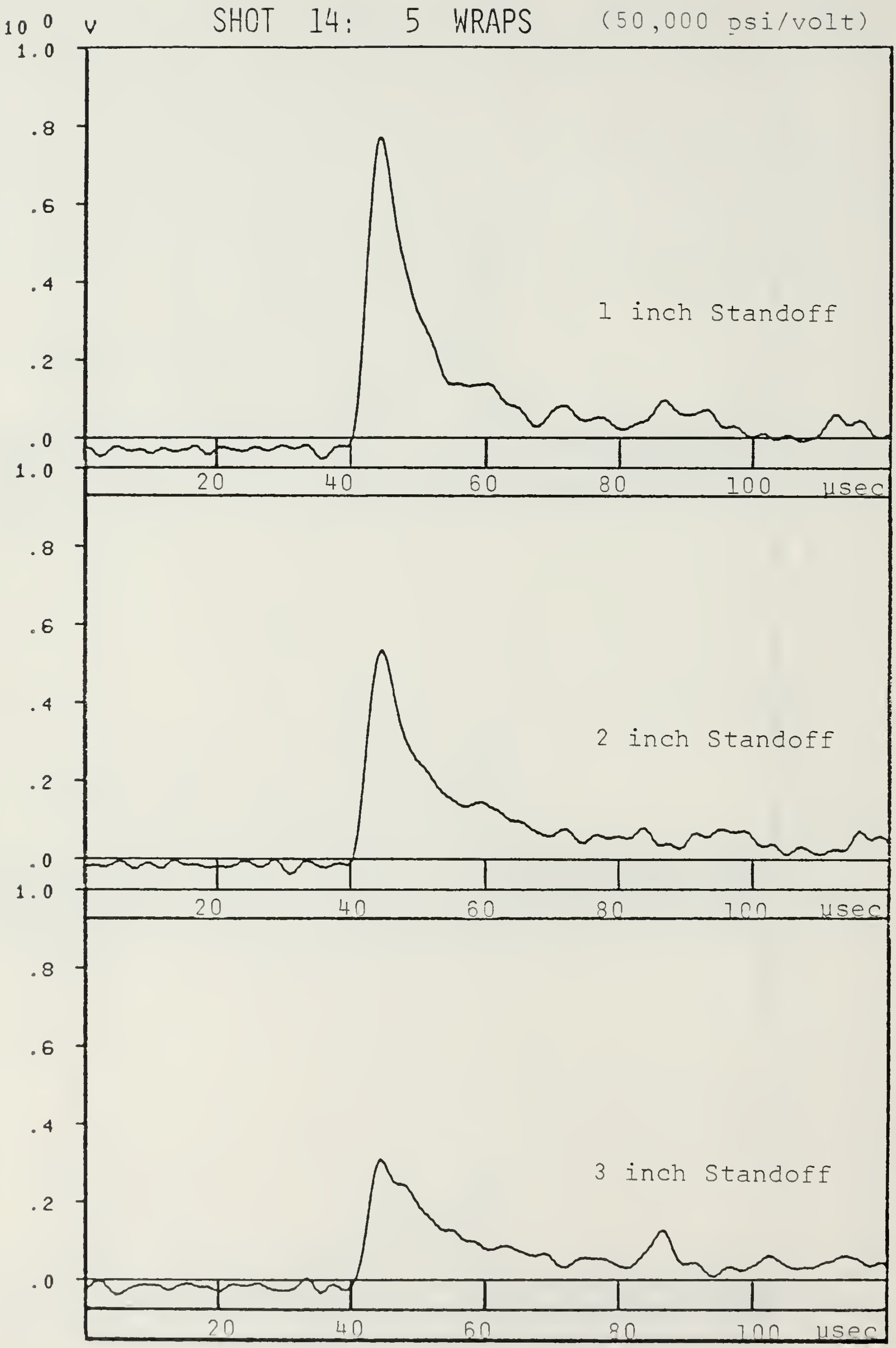
EXPERIMENTAL PRESSURE/TIME HISTORIES



SHOT 12: 1 WRAP
(50,000 psi/volt)
10^{-1} V
5.0
4.0
3.0
2.0
1.0
.0
1 inch Standoff
2 inch Standoff
3 inch Standoff
20
40
60
80
100
μsec

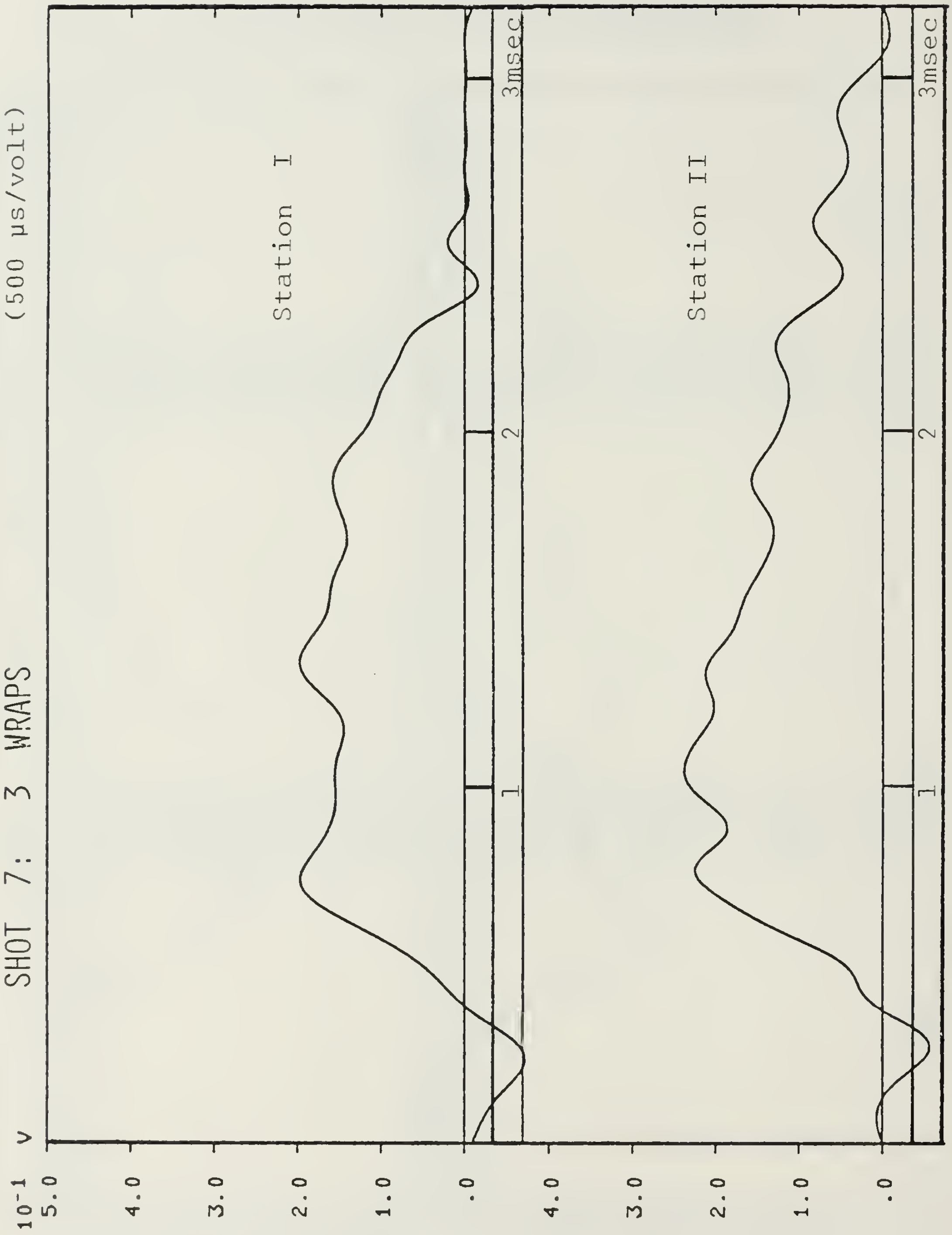


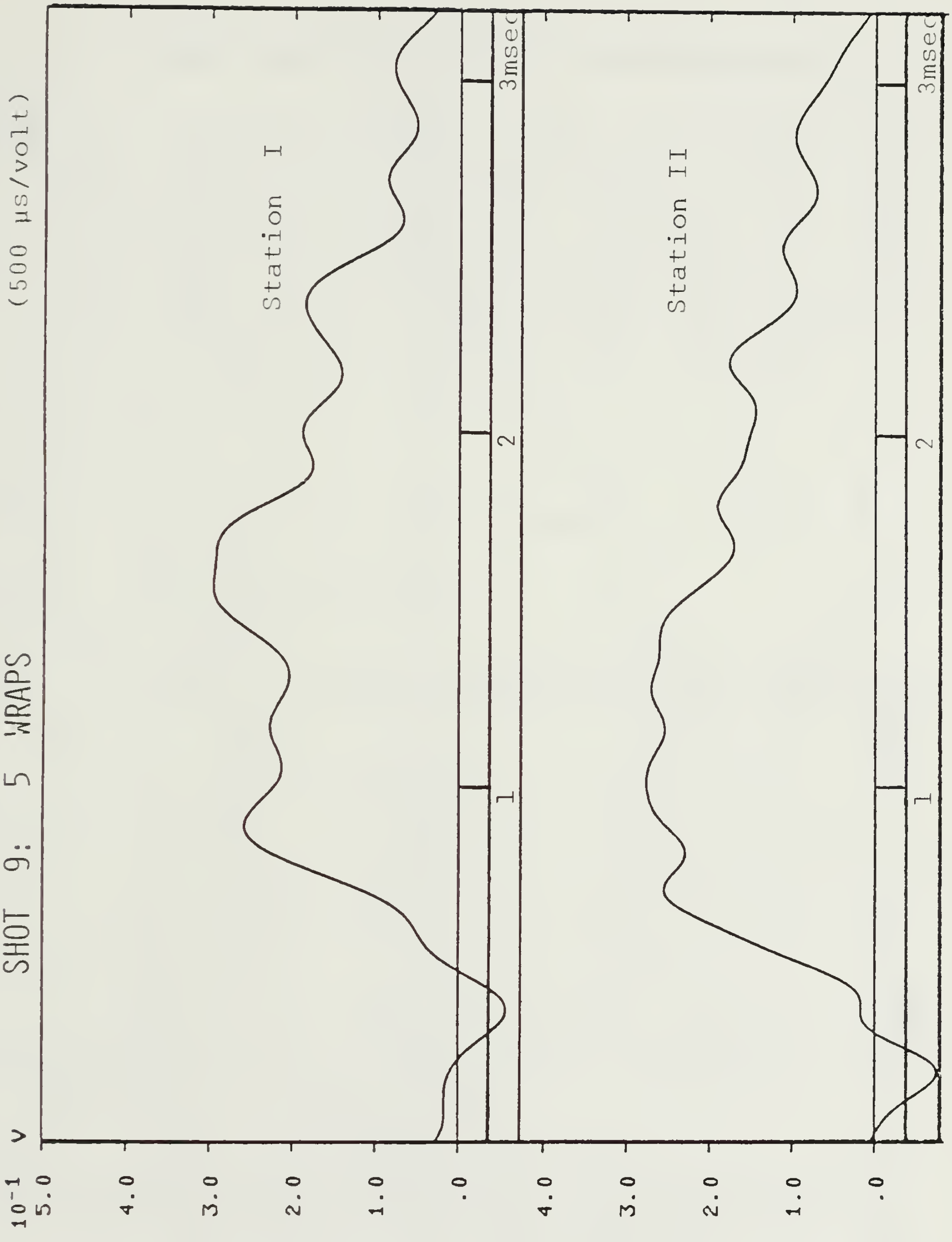
SHOT 13: 3 WRAPS
(50,000 psi/volt)
10 0 V
1.0
.8
.6
.4
.2
.0
1 inch Standoff
2 inch Standoff
3 inch Standoff
20
40
60
80
100
µsec

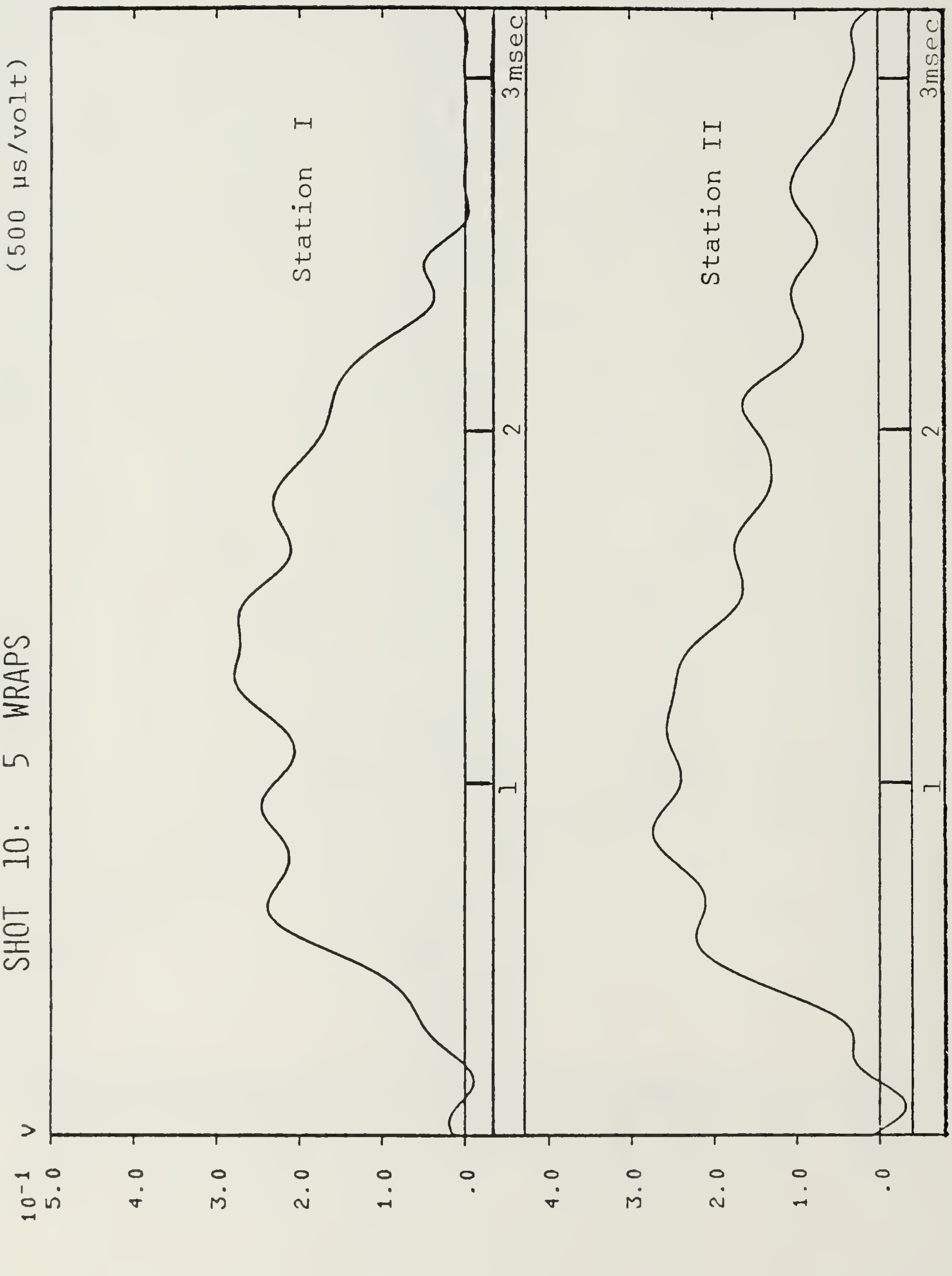

SHOT 14: 5 WRAPS (50,000 psi/volt)
10 0 V
1.0
.8
.6
.4
.2
.0
1 inch Standoff
2 inch Standoff
3 inch Standoff
20
40
60
80
100
μsec

APPENDIX B

EXPERIMENTAL STRAIN WAVE HISTORIES


SHOT 7: 3 WRAPS
(500 µs/volt)
Station I
Station II
3msec
2
1
3msec
2
1
10-1
5.0
4.0
3.0
2.0
1.0
.0
4.0
3.0
2.0
1.0
.0
V


SHOT 9: 5 WRAPS
(500 μs/volt)
Station I
Station II
V
10⁻¹ 5.0
4.0
3.0
2.0
1.0
.0
1
2
3msec


SHOT 10: 5 WRAPS
(500 µs/volt)
Station I
Station II
1
2
3msec
v
10-1
5.0
4.0
3.0
2.0
1.0
.0

APPENDIX C

AXIAL FORCE BY NUMERICAL INTEGRATION

```
C Numerical integration of the incident and reflected
C     pressure over the area of the propeller hub of
C     ex-USCGC CAMPBELL (WHEC-32) as a function of
C     time after start of the detonation process.
      REAL R(41), T(1001), P(41,1001), F(1001), PM(41)
      REAL C, THETA, PSUM(41), FSUM(1001), FTOT(1001)
C Integration step sizes (inches):
      HR = 0.1
      HPHI = 0.06
C Speed of sound in water (inches/msec)
      C = 5.0*12.0
C Average time constant (msec):
      THETA = 0.012
C Peak pressure vs. DETCORD standoff along hub radius (psi):
      DO 11 I = 1,41
         R(I) = FLOAT(I-11)/10.0
C1  One-wrap charge:
C        PM(I) = 2.*{0.75*[R(I)**2] - 7.75*[ABS(R(I))] + 24.0}
C3  Three-wrap charge:
C        PM(I) = 2.*{1.125*[R(I)**2] - 12.625*[ABS(R(I))] + 40.0}
C5  Five-wrap charge:
         PM(I) = 2.*{1.5*[R(I)**2] - 17.5*[ABS(R(I))] + 56.0}
C Pressure as function of time for each increment of radius dR:
         DO 12 J = 1,1001
            T(J) = (FLOAT(J) - 1.0)/1000.
            TD = T(J) - ABS(R(I))/C
            P(I,J) = PM(I)*EXP[(-TD)/THETA]
               IF(TD.LT.0.0)P(I,J) = 0.0
   12    CONTINUE
   11 CONTINUE
```

```
C SIMPSON'S Integration of unit force over R = -1 to 3 inches:
      DO 21 J = 1,1001
      PSUM(1) = P(1,J)
      PSUM(41) = P(41,J)
      F(J) = 0.0
         DO 22 I = 2,40,2
            PSUM(I) = 4.0*P(I,J)
   22    CONTINUE
         DO 23 I = 3,39,2
            PSUM(I) = 2.0*P(I,J)
   23    CONTINUE
         DO 24 I = 1,41
            F(J) = F(J) + PSUM(I)*HR/3.0
   24    CONTINUE
   21 CONTINUE
C
C SIMPSON'S Integration of F(t) from t = 0.0 to 0.1 msec:
         FTOT(1) = F(1)*HPHI
         FTOT(2) = (F(1)+F(2))*HPHI
         WRITE(6,61)(T(J),FTOT(J),J = 1,2)
   61    FORMAT(2(E15.6))
      DO 31 K = 3,1001
         FTOT(K) = 0.0
         N = 1
         IF(K.GT.655)N = K-654
         N2 = N+2
         K2 = K-2
         N1 = N+1
         K1 = K-1
         FSUM(1) = F(1)
         FSUM(K) = F(K)
         IF(K.LE.2)GO TO 331
         DO 32 J = N1,K1,2
            FSUM(J) = 4.0*F(J)
   32    CONTINUE
```

```
      IF(K.LE.3)GO TO 331
      DO 33 J = N2,K2,2
         FSUM(J) = 2.0*F(J)
 33   CONTINUE
331   DO 34 J = N,K
         FTOT(K) = FTOT(K) + FSUM(J)*HPHI/3.0
            IF(K.EQ.657)FTOT(K) = FTOT(656)
 34   CONTINUE
    WRITE(6,60)T(K),FTOT(K)
 60 FORMAT(2(E15.6))
 31 CONTINUE
C
    STOP
    END
```

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